

# LHC: Energy Sensitive Machine Issues

Tom Taylor  
CERN

VLHC, Monterey, June 1999

# Project Goals

- Provide design luminosity ( $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ) at design energy (7+7 TeV)

- **Schedule**

- 1999 - complete R+D on models and prototypes
- 1999 - order full-size pre-series magnets
- 2001 - 2004 - produce and test magnets
- 2005 - start commissioning machine

**2 to 3 years to reach design parameters**

# History

(1)

- 1984 ECFA-CERN workshop (LHC in LEP tunnel)
- 1987 report CERN 87-05

- p-p 8TeV per beam, peak  $L = 1.4 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$   
(proton-antiproton  $10^{31}$  )
- (p-electron, 8TeV-65GeV  $10^{32}$   
-100GeV  $10^{31}$  )

8-10 T twin-aperture magnets 40 -> 50 mm aperture  
based on NbTi conductor at 1.8 K (or Nb<sub>3</sub>Sn at 4.5 K)  
(Beam crossing angle = 2 \* 48 microradian)

# History

(2)

- 1991 Design Study "Pink Book" (CERN 91-03)  
(A multiparticle collider in the LEP tunnel)

- p-p 7.7TeV per beam, peak  $L = 1.65 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$   
(ions  $1.8 \cdot 10^{27}$  )
- (p-electron 7.7TeV-60GeV  $2.8 \cdot 10^{32}$  )

10 T twin-aperture magnets, 50 mm aperture,  
beam separation 180 mm, magnetic length 9 m,  
based on NbTi conductor at 2 K

(Beam crossing angle =  $2 \cdot 100$  microradian)

# History

(3)

- 1993 LHC “White Book” (CERN/AC/93-03)  
(The Large Hadron Collider Accelerator Project)

- p-p 7 TeV per beam, peak  $L = 1 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- (ions  $1.8 \cdot 10^{27}$  )
- (p-electron - preserve for future e-p collisions )

8.65 T twin-aperture magnets, 56 mm aperture,  
beam separation 180 mm, magnetic length 13.145 m,  
NbTi conductor at 1.9 K

# History

(4)

- 1995 LHC “Yellow Book” (CERN/AC/95-05)  
(The Large Hadron Collider - conceptual design)

- p-p 7 TeV per beam,      peak  $L = 1 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- (ions       $> 1 \cdot 10^{27}$  )
- (p-electron - “preliminary work” ->  $> 1 \cdot 10^{32}$  )

8.4 T twin-aperture magnets, 56 mm aperture,  
beam separation 194 mm, magnetic length 14.2 m,  
NbTi conductor at 1.9 K. Introduce cryoline.

(Beam crossing angle =  $2 \cdot 100$  microradian)

# Present Day

- June 1999 “version 6.1” ( Web )

- p-p 7 TeV per beam, peak  $L = 1 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- (ions  $1.8 \cdot 10^{27}$  )
- (p-electron - not excluded in distant future )

8.4 T twin-aperture magnets, 56 mm aperture,  
beam separation 194 mm, magnetic length 14.3 m,  
NbTi conductor at 1.9 K.

(Beam crossing angle =  $2 \cdot 150$  microradian)

# Description of main dipole

- **Design is a 2-layer graded  $\cos \theta$  coil, supported in a single rigid collar**
  - the coil design resembles that used successfully for other recent high-field dipoles (LHC, SSC, HERA)
  - the twin-aperture design (which originated at BNL) is appropriate (necessary) for LHC in the LEP tunnel
- **status**
  - models perform fairly well
  - long magnets “just make it” - but will improve!



# Concept of "Ultimate" working conditions

- Design all equipment which should be installed for the expected duration of operation of the LHC to be capable of working at 7.7 TeV, nominal intensity, or 7 TeV, with increased ( $\sim \times 2$ ) intensity.
- At this level there is no safety margin
  - the dipole should be trained up to 9 T, no more
  - the cryogenic system should handle the load (just)
  - the customary 10% safety margin in power converters should only apply to the nominal conditions
  - etc.

# Energy limiting factors

The energy of the LHC is essentially limited by its installation in the existing **LEP tunnel**

- > Synchrotron radiation load

- > increase cryogenic power ...

(But the potential is small, given the fourth power law ( $< 8$  TeV) and the **increased radiation** could also pose a problem concerning the lifetime of electronics in the tunnel)

Another limitation is the **Electron Cloud Effect**

- > surface condition; beam cleaning

# R+D for the future (1)

The **KEK team** has a reputation for innovation in the use of materials in superconducting magnets

- e.g. high Mn steel (low permeability), and
- high strength high RRR aluminium (for stabilizing conductor used in large magnets).

Future quadrupoles of improved performance (e.g. having the same gradient in a larger aperture) may one day be required for upgrading the performance of the inner triplets.

In collaboration with the National Research Institute for Metals (Tsukuba), the team is investigating the use of multi-filamentary  $\text{Nb}_3\text{Al}$ , which has several attractive features as compared to  $\text{Nb}_3\text{Sn}$  for use in high field magnets.

# R+D for the future (2)

The **University of Twente** designed and built for CERN a 1 m long model of an LHC dipole using Nb<sub>3</sub>Sn conductor cabled from wires produced using the PiT process.

This model performed very well.

A further contract has therefore been placed with them for the design and manufacture of a 1 m model of a single aperture dipole which could, in a future phase of the LHC replace the separation dipole closest to the IP (to provide larger aperture in a shorter length). The challenges are

- to reduce the filament size from ~30 to ~20 micron
- to make tooling suitable for a full-length (~8 m) magnet
- to reproduce the success of the first model!

# LHC experience - (a personal view)

Work was started on the LHC in the early eighties.

As with all projects, mistakes have been made.

Some can be attributed to sheer political expediency,  
others to over optimistic extrapolations,  
but most could have been avoided

(with 20/20 hindsight!)

With the project now in full swing,  
and with history still recent enough,

this forum provides a good opportunity to describe

some of the problems...

# The Dipole

**Field.** LHC was “pushed” (race with SSC) into starting with too little margin.

We all know that 20% margin is “reasonably” minimum...

**Dynamic range.** The LHC has x16. This makes life hard.

I would aim for x10 for a VLHC - unless you can get large aperture “for free”.

**Aperture.** LHC started with 50 mm and went to 56 mm : with our dynamic range, 60 mm would be more comfortable

**Length.** To reduce field, and total number of costly ends, we went from units of 10 m to 14.2 m in length.

The consequences were not evaluated fully.

(sagitta, support system, correction pack, etc.)

# (Value ) Engineering

**Incorporate “engineering” into the R&D from the beginning!**

In the case of the LHC dipole

- time constraints
- aiming too high

interfered with the engineering process.

A number of aspects were recognized as “needing attention” but were left until later (and have inevitably remained...)

## **Use of industry**

As concerns the magnets, industrial participation was introduced (too?) early, supposedly for “industrial input” (but also to get political support for LHC)

**- Industry did not innovate!**

**\*\*\* Do the magnet R&D in the lab. \*\*\***

# Time

**Admit that these are 20-year projects**

R&D on the LHC dipole suffered from a constant  
**need to show that we were ready for production**  
(justified(?) on political grounds)

Better approach:

break into 3 (~equal) phases

- **exploratory R&D + value engineering**
- **value engineering + targeted R&D (->construction approval)**
- **production + installation**

**BUT work should be intense during each phase (milestones)**

Alternatively use “**pilot project**” (also good for HR)



# Human resources

Historically, HR management at CERN has been poor.

A 15-year "hole" in recruitment meant that we lost the opportunity to train young engineers who are now expected to take responsibility for large systems and handle big contracts, without having had experience of smaller CERN projects.

The **Pilot Project** idea might have helped. In our case this could for example have been an SPS upgrade (to 1+ TEV)...  
(With maybe a Cp violation experiment, if it had been a twin aperture machine)

## International collaboration

We were nervous about this at first - but it **works very well**.

- **Helps to solve the HR problem**
- **We have to (politics/approval/maintenance of approval)**

So, make a virtue of necessity - and **start early** !

# CERN and the VLHC

As concerns the LHC Division at CERN the idea is to collaborate at a level commensurate with current commitments.

This should present 2-way benefit.

In a sense the LHC can be considered as a Pilot Project for the VLHC, particularly with regard to such issues as

- accelerator physics
  - magnet design
  - cryogenics
  - vacuum
  - instrumentation
- etc.

# Something on **Accelerator Physics**

The US laboratories and CERN are collaborating on various studies relating to the definition and operation of the LHC. These studies are obviously of direct interest to the VLHC, and concern in particular

- **the dynamic aperture**
- **the beam-beam effect**
- **beam crossing schemes**

For example, the beam-beam workshop which was held recently at CERN drew attention to the importance of the long-range beam-beam effect, and to the phenomenon of the inevitable “pacman” bunches.

## Something on Vacuum

Recent work at CERN indicates that it may be possible to make a big stride forward as concerns the ultra-high vacuum for the VLHC, by way of using non-evaporable getter (NEG) pumping.

C. Benvenuti and P. Chiggiato (EST Division) report good results of TiZr and TiZrV NEG coating on st. steel vacuum chambers.

The TiZrV coating is especially interesting - it can be activated with a 24 hour bake at 150°C (50°C less than the TiZr coating), leading to the hope that it could be used for an AI chamber.